

Integral Bypass Diodes in an Amorphous Silicon Alloy Photovoltaic Module

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Thin-film, tandem-junction, amorphous silicon (a-Si) photovoltaic modules have been constructed in which a part of the a-Si alloy cell material is used to form bypass protection diodes. This integral design circumvents the need for incorporating external, conventional diodes, thus simplifying the manufacturing process and reducing module weight.

Introduction

When connecting photovoltaic cells in series, each cell is potentially vulnerable to damage caused by inadvertent application of a reverse bias having a voltage equal to the sum of the voltages produced by the other cells in the string. This occurs either when the cell is shaded while the others are illuminated, or if the current of the cell is not matched well to that of the other cells. This reverse voltage, if sufficiently high, can cause breakdown, leading to irreversible damage in the shaded cell. To protect against this event, diodes are usually connected across one of several cells in order to prevent build-up of this reverse voltage (see Figure 1). These "bypass" diodes are necessary, but they lead to increased cost and complexity in module fabrication and they add extra weight to the module, which can reduce significantly the power-to-weight ratios, particularly for an ultralight module. Accordingly, alternative solutions to solar cell protection are in order. Integral bypass diodes, made of the same material and on the same substrate as the solar cell are particularly attractive for this purpose. Previous examples of integral diode design exist for individual monocrystalline silicon cells, which incorporated the bypass diode on a portion of the wafer [see, e.g., refs. 1 and 2]. Recently, thin film integral bypass diodes made of a-Si have been described by Ishihara et al. [ref. 3].

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The purpose of this paper is to describe our experimental results on integral, tandem-junction a-Si bypass diodes protecting a series string of a-Si tandem-junction solar cells and to evaluate them for potential use in ultralight space PV arrays. We have found the current-carrying capability of the a-Si alloy diodes to be excellent, allowing the diode to be fabricated on a relatively small area of the active solar panel.

Results and Discussion

Determination of Damage Induced by Reverse Bias in Unprotected a-Si Alloy Cells

At first we conducted experiments to determine the minimum number of a-Si alloy solar cells connected in series that would lead to module damage upon shadowing of one of the cells. The experiments have been conducted on modules consisting of commercially available Sovonics tandem-junction, n-i-p/n-i-p cells, 14.5 cm² in area, deposited on a stainless steel substrate and encapsulated in a flexible polymer. Series strings from two to 32 such cells were made, short-circuited, exposed to AM1.5 illumination, and selected cells were shadowed one at a time. The unshaded cells thus applied external reverse bias of 1.6 to 49.6 V to the shaded cell.

The minimum number of cells per string in which damage was observed was four; in this case a decrease of 300 mV in V_{oc} as well as a decrease in the fill factor took place. With larger number of cells per string the damage was progressively more frequent and more severe.

A shadowing experiment has also been made on a monolithic [ref. 4], Ultralighttm [refs. 5 and 6] module consisting of 120 tandem-junction cells, each 6.3 cm in area (12 cells per series string x 10 strings in parallel). After shadowing of all cells, 10 cells at a time, the V_{oc} decreased by 2.8 V from 16 V to 13.2 V.

In still another experiment over 350 such 6.3 cm² cells were connected in series, generating V_{oc} in excess of 500 V. Without bypass diode protection, several of the cells sustained visible burns just by operating the module in the sunlight without shadowing.

These experiments clearly indicate that bypass diode protection is desirable with a-Si alloy cells across at least every 3 tandem-junction cells connected in series and preferably across every cell.

Determination of Current Carrying Capacity of a-Si Alloy Tandem-Junction Diodes

Next, we carried out tests to determine the maximum current which these diodes, made of tandem-junction, a-Si alloy cell material, could carry without heating up to temperatures which could damage either them or other parts of the module, such as

the encapsulant. To do this, the diodes were made having an area of 1.28 cm^2 and a top contact of silver paste covering completely the transparent indium tin oxide electrode. The diodes being tested were placed in a small oven and the instantaneous I-V curve was scanned at various temperatures. One typical result is shown in Figure 2. (The temperature coefficient (dV/dT) in Figure 2 is approximately $20 \text{ mV}/^\circ\text{C}$, which is larger than expected [ref. 7]. This behavior will be addressed in a future publication.) The diodes were then placed at ambient temperature and a DC voltage was applied until the diode reached its steady-state operating temperature. The I-V curve was then scanned and the diode temperature was deduced by correlation of this scan to one of the scans in Figure 2. It was found that the diodes were capable of passing an instantaneous current of $7 \text{ amps}/\text{cm}^2$ at 6 volts. They were able to sustain in excess of $1\text{-}1.5 \text{ amps}/\text{cm}^2$ at 2.53 volts without exceeding a temperature of approximately 100°C in air.

Demonstration of Effective Protection of PV Modules with a-Si Alloy Bypass Diodes

In order to test the effectiveness of the diodes in a module, we performed a test aimed at demonstrating that as the cell was progressively shadowed, less current was generated by the cell, while an increasing amount of current was passing through the diode. The circuit shown in the inset of Figure 3 was constructed with a standard, 2.5 watt module consisting of seven cells interconnected in series and protected with conventional silicon diodes. One of these diodes was removed and replaced with an a-Si alloy, tandem-junction diode having a multilayer structure similar to that of the cells used in the module. The size of each cell was 74 cm^2 while that of the a-Si diode was 1 cm^2 , so that the ratio of the diode area to that of the module was 1.4%. The module was then exposed to near-AM1 solar irradiation and with the output leads of the module shorted, the current generated by the module and the current passing through the a-Si alloy bypass diode were measured (I_1 and I_2 in Figure 3). Figure 3 reflects the desired result that increasing shadowing effects both a decrease in cell current (obtained by subtracting I_2 from I_1) and an increase in diode current. The string current (I_1) remains essentially independent of shadowing, as is required for a module which is properly protected. The nonlinearity in the curves for weak shadowing arises from the finite turn-on voltage of the diode. Since the diode has a tandem junction, its turn-on voltage is approximately twice that of a single junction diode. Therefore, until sufficient shadowing and concomitant build-up of reverse voltage occurs, current will not flow through the bypass diode and will instead flow through the shadowed cell, causing a reduction in the total string current.

Protection of Large a-Si Alloy Cells with Integral a-Si Alloy Diodes

After this test, we fabricated a module in which the diodes were integrally formed. The module consisted of four giant tandem n-i-p/n-i-p cells, each having an area of 1430 cm^2 . Diodes were created on a 6.25% portion of each of these cells and were

separated from the active cell area by etching through the top conductive layer to form a thin border line. The bypass diode on a given cell substrate was connected so as to protect the cell on the adjacent substrate.

Figure 4 shows the I-V curve for the module both with and without shading of one of the cells. Note first that there is a difference of about 1.7 V in open circuit voltage between the two curves (6.6 V-4.9 V); this is consistent with the fact that the contribution of the shaded cell (1.6 to 1.7 V) is removed upon shading. At voltages less than that at open circuit, the discrepancy in voltage between the two curves is approximately 4 V. This occurs because the voltage in the cell string does not sufficiently bias the diode (thus decreasing its conductivity), causing the diode to act as an internal resistance. For example, for a module output voltage of 2 V, the diode would be forward biased 2.9 V (4.9 V-2 V). From Figure 2, this corresponds to 1 to 5 amps, depending on temperature, which is consistent with the string current of 3 A generated during shading (Figure 4). It is this factor which is also responsible for the decrease in the fill factor for this curve.

Figure 4 also shows that the original I-V trace is essentially reproduced after the shading has been removed, signifying that the diodes had indeed protected the module. (The reduction in V_{oc} of about 0.1 V is probably due to a slight heating of the module [ref. 7].) Considering the diode current-carrying capability discussed above, one could optimally construct an integrally, diode-protected version of one of these large cells with about 10 cm², or 0.7% (10 cm² /1430 cm²) of the cell area devoted to the bypass diode.

Another, similar, two-cell module containing integrated bypass diodes was connected in series to a Sovonics MP140 panel (consisting of 14 cells, each 1430 cm² in area, all connected in series) and exposed to direct sunlight to produce a total array I_{sc} of 10.2 A and V_{oc} of 24.9 V. Each of the cells in the two-cell module was sequentially shaded while the whole array was held at short circuit. The I_{sc} and V_{oc} readings with one cell shaded were 10.13 A and 23.3 V. Note that the difference in V_{oc} readings is 1.6 V, (24.9 V-23.3 V), again signifying a reduction in voltage by an amount equal to the V_{oc} of the shaded cell. Once again, no degradation in either the short circuit current or open circuit voltage of the module was observed after the shading was removed. Without bypass diodes damage by such a high reverse bias (23.3 V) would be expected to occur and even more readily in the large cells used in the present test because of the 20 to 200 times larger photocurrent generated by these large cells.

Finally, it is useful to compare the behavior of the thin film, a-Si alloy tandem-junction diode with its conventional silicon diode counterpart. Figure 2 shows that 3 to 4 V bias is needed in order for the a-Si diodes to pass 5 amps. This value compares with about 1.2 V for a conventional silicon diode. This fact may make the use of thin film diodes advantageous, since short passivation of a-Si alloy tandem junction solar cells is optimally carried out by applying a reverse bias of about 5 V. Therefore, an

occasional build-up of several volts on a cell during shadowing may actually act to repair any shorts which may exist within the cell [ref. 8]. We have demonstrated this feature in a separate experiment. We have also shown that in general, this reverse bias voltage is not sufficiently high to create new shorts by causing cell breakdown; these shorts are typically created above about 5 V.

Conclusions

In conclusion, we have shown that protection of a-Si alloy tandem junction photovoltaic cells in solar panels against reverse bias voltage can be achieved through the use of integrated bypass diodes made of the same materials as the solar cells. Protection of a cell area as large as 1430 cm² has been demonstrated. This capability has important implications on the design and manufacture of ultralight, monolithic arrays for potential space applications [refs. 5 and 6] as well as in arrays utilizing "giant" cells [ref. 9]. It will also have a substantial impact on the reliability and production cost of any amorphous silicon alloy panels, using either single junction or multijunction cells.

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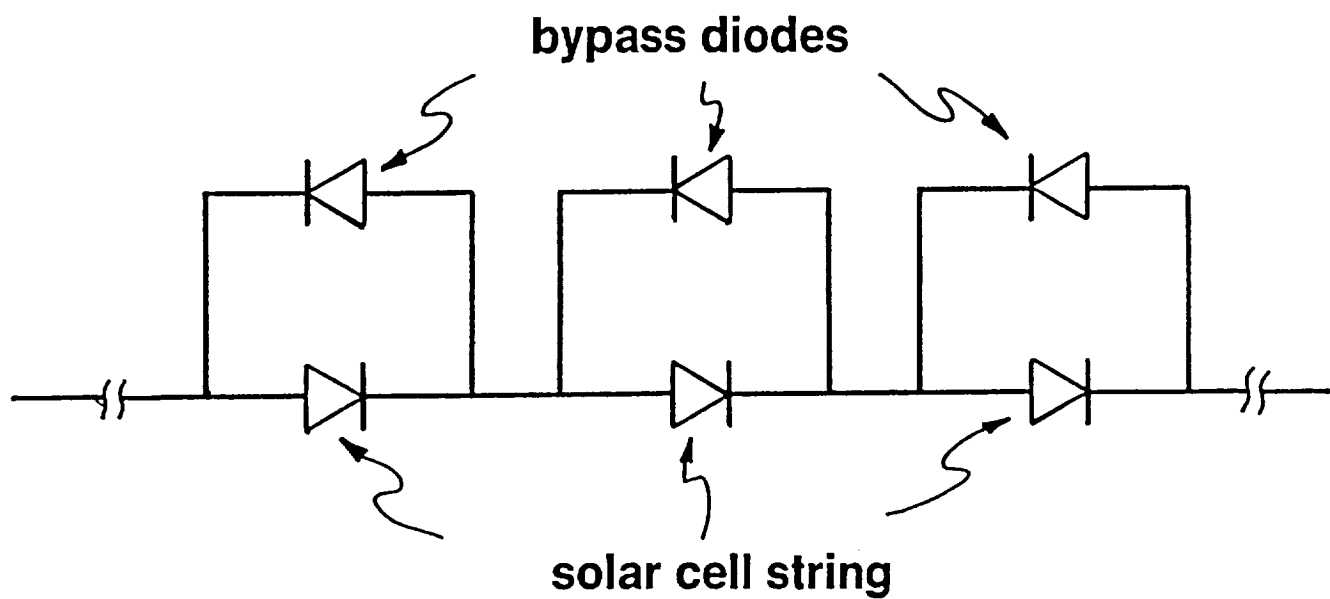


Figure 1 Schematic diagram showing how bypass diodes are connected to a string of solar cells (also represented as diodes).

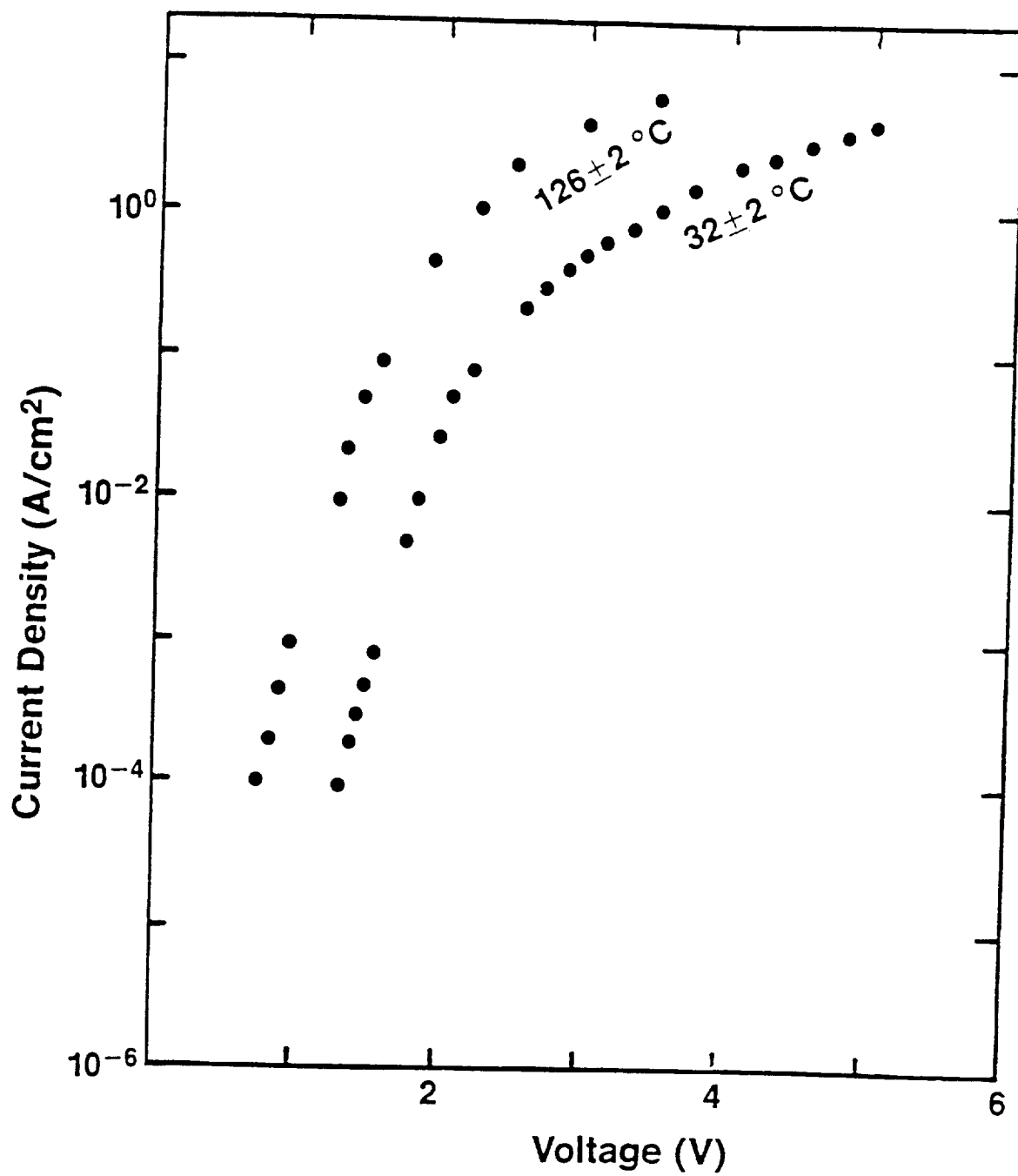


Figure 2 Typical dark I-V characteristics for an a-Si alloy tandem-junction cell, recorded at two temperatures.

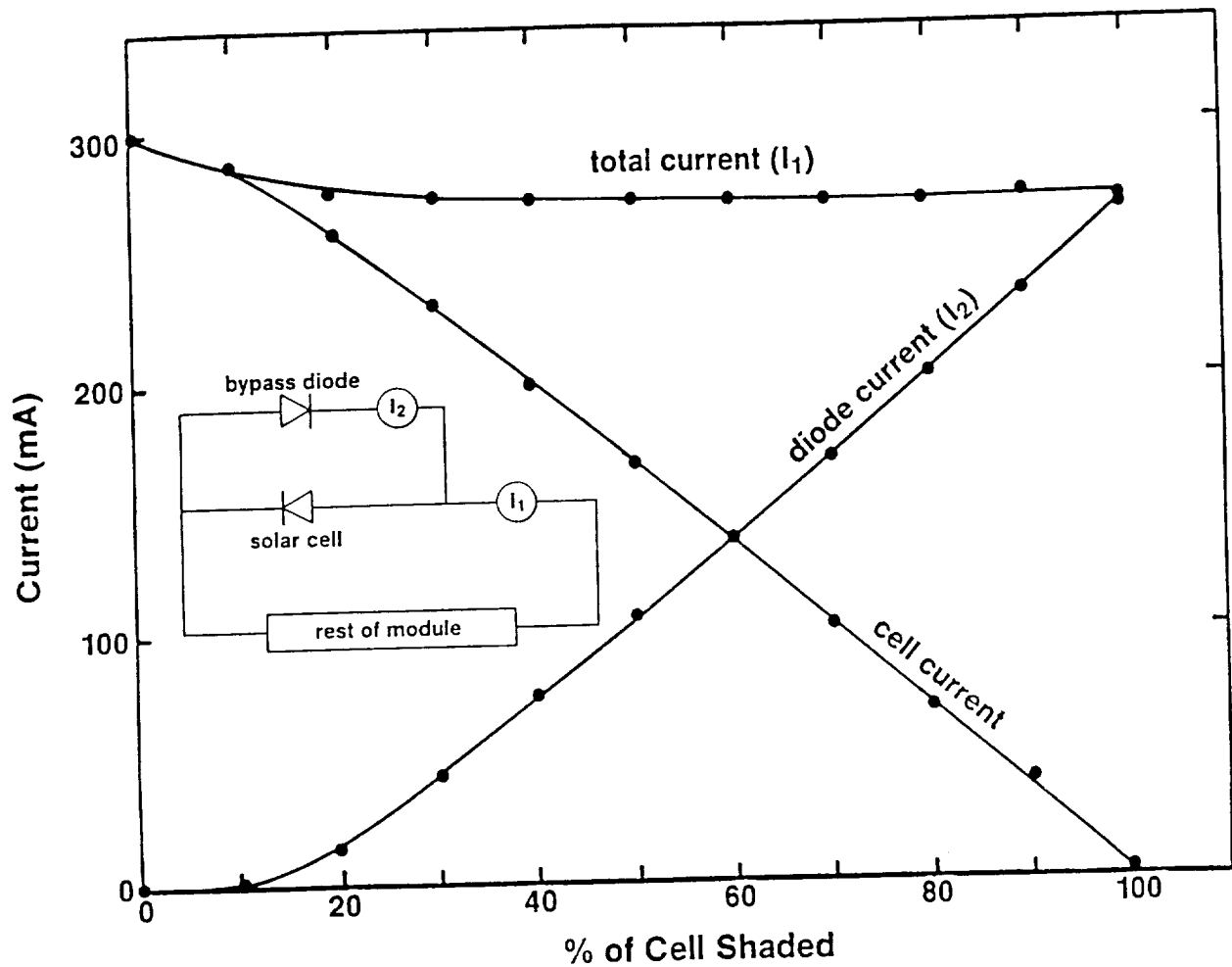


Figure 3 Total, diode and cell current vs. percentage of the cell shaded, using an a-Si alloy tandem-junction bypass diode. The cell current was obtained by subtracting the diode current from the total current, which were measured using the circuit shown in the inset.

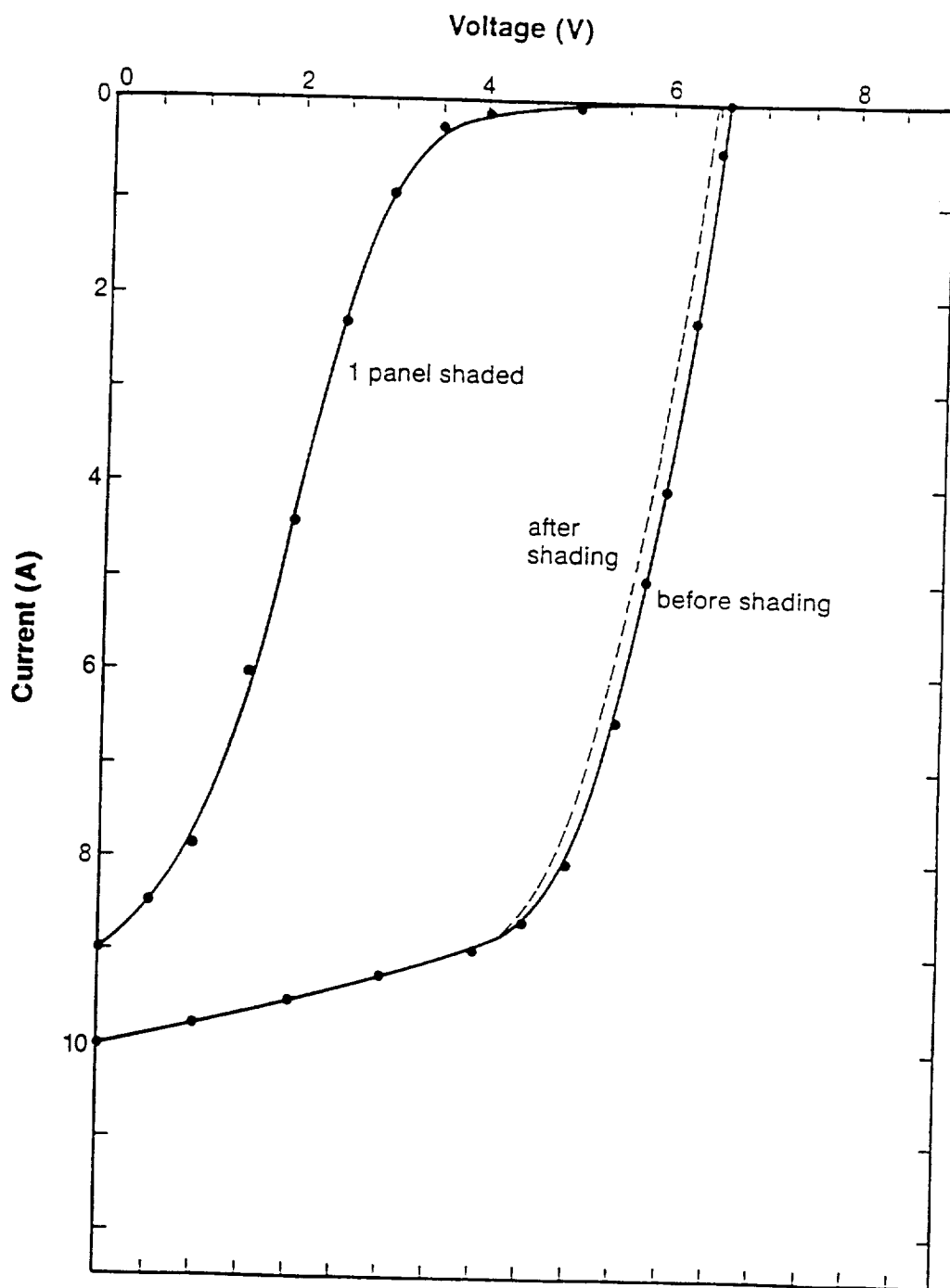


Figure 4 Current vs. voltage for a four-cell module protected with a-Si alloy tandem junction diodes (AM1 intensity). The dotted line represents the scan carried out after the shading of one of the cells.